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# Snowflake divertor - a possible power exhaust solution for magnetic fusion.

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Washington, DC, United States  
December 5, 2012 through December 6, 2012

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# Snowflake divertor – a possible power exhaust solution for magnetic fusion

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**NSTX-U and DIII-D Research Teams**

FUSION POWER ASSOCIATES  
33<sup>rd</sup> Annual Meeting and Symposium  
Fusion Energy: Progress and Promise  
December 5-6, 2012  
Washington, DC 20003

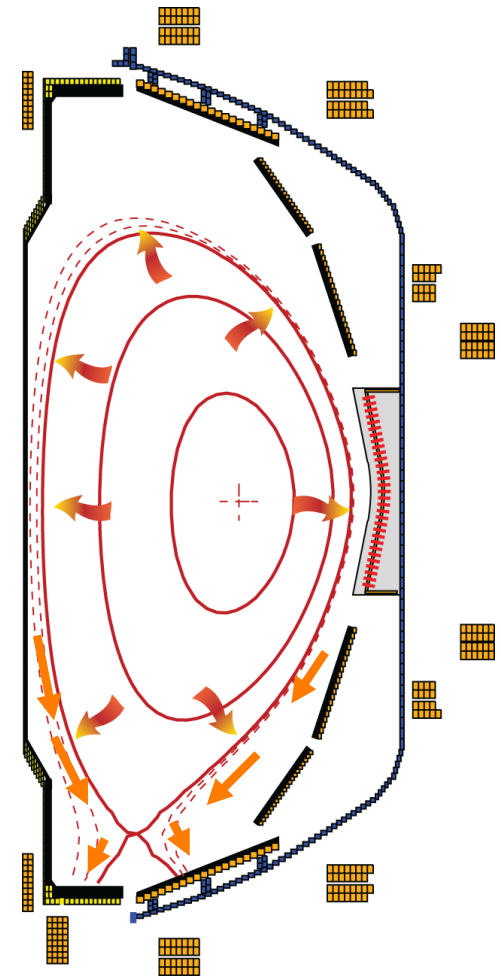
# Acknowledgements

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- **LLNL Theory:** D. D. Ryutov, T. D. Rognlien, M. V. Umansky
- **NSTX-U Team:** D. Battaglia, R. E. Bell, A. Diallo, S. P. Gerhardt, R. Kaita, S. M. Kaye, E. Kolemen, B. P. LeBlanc, R. Maingi, McLean, E. Meier, J. E. Menard, D. Mueller, S. F. Paul, M. Podesta, R. Raman, A. L. Roquemore, F. Scotti
- **DIII-D Team:** S. L. Allen, J. Boedo, N. Brooks, M. Fenstermacher, R. Groebner, D. N. Hill, A. Hyatt, C. Lasnier, A. Leonard, M. Makowski, A. McLean, T. Osborne, T. Petrie, J. Watkins
- **DOE OFES:** This work supported in part under Contract DE-AC52-07NA27344

# Poloidal divertor concept enabled progress in tokamak physics studies in the last 30 years

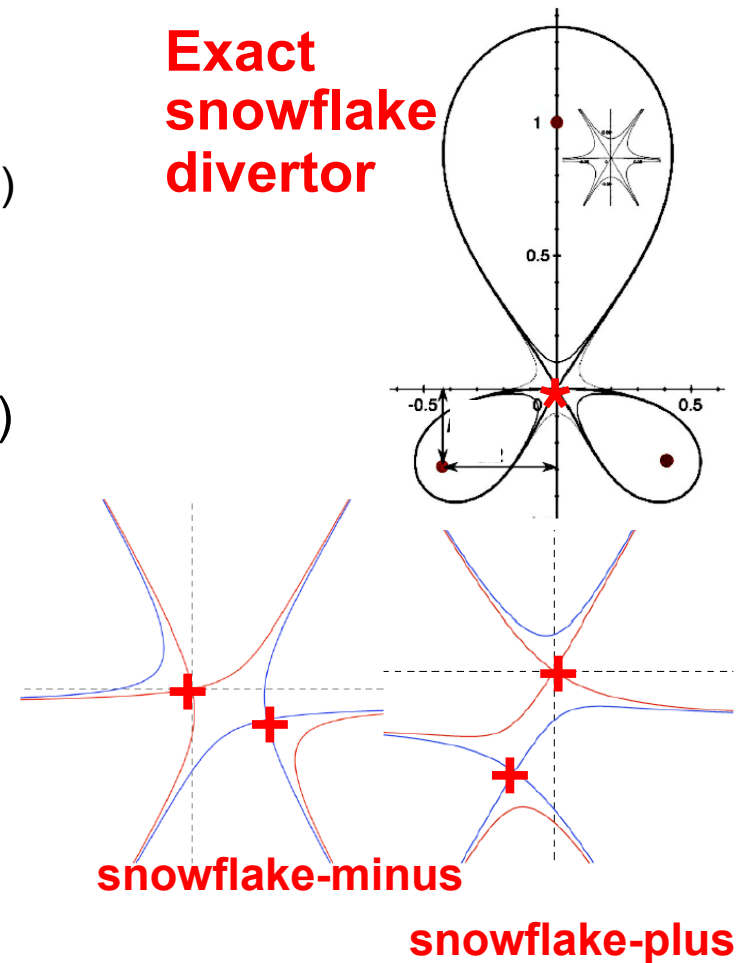
- Divertor challenge
  - Steady-state heat flux
    - present limit  $q_{peak} \leq 10 \text{ MW/m}^2$
    - projected to  $q_{peak} \leq 80 \text{ MW/m}^2$  for future devices
  - Density and impurity control (low  $T_e$ )
  - Impulsive heat and particle loads
  - Compatibility with good core plasma performance
- NSTX (Spherical Tokamak, aspect ratio  $A=1.4-1.5$ )
  - $I_p \leq 1.4 \text{ MA}$ ,  $P_{in} \leq 7.4 \text{ MW}$  (NBI)
  - $q_{peak} \leq 15 \text{ MW/m}^2$ ,  $q_{||} \leq 200 \text{ MW/m}^2$
  - Graphite PFCs with lithium coatings
- DIII-D (Conventional tokamak, aspect ratio  $A \sim 2.7$ )
  - $I_p \leq 1.5 \text{ MA}$ ,  $P_{in} \leq 20 \text{ MW NBI} + 3.6 \text{ MW ECH}$
  - $q_{peak} \leq 10 \text{ MW/m}^2$
  - Graphite PFCs



**National Spherical  
Torus Experiment  
at PPPL**

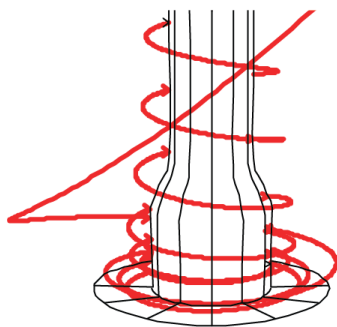
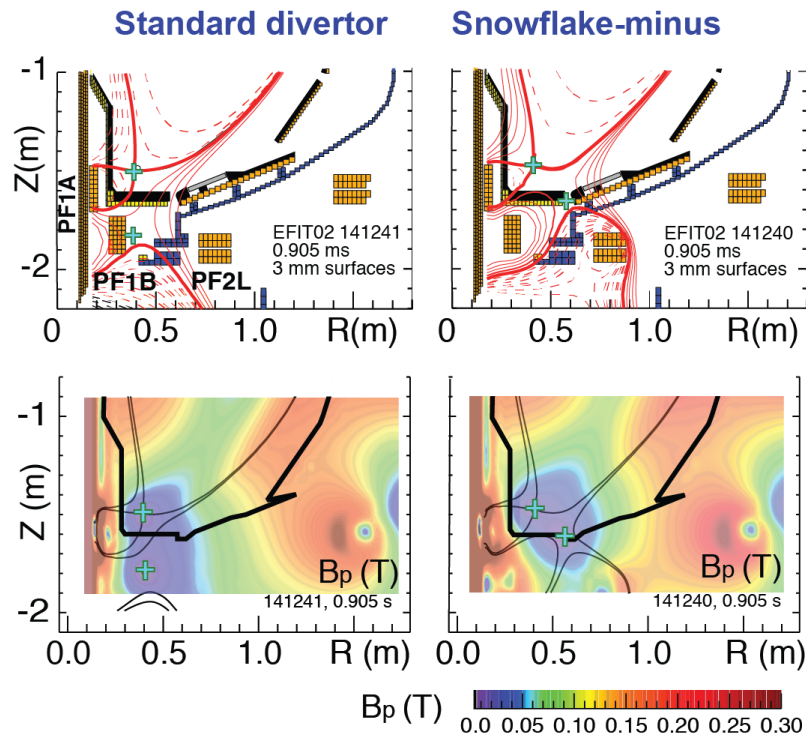
# Snowflake divertor configuration predicted to have significant benefits over standard X-point divertor

- Snowflake divertor
  - Second-order null
    - $B_p \sim 0$  and  $\text{grad } B_p \sim 0$  (Cf. first-order null:  $B_p \sim 0$ )
  - Obtained with existing divertor coils (min. 2)
  - Exact snowflake topologically unstable
- Predicted geometry properties (cf. standard divertor)
  - Increased edge shear: ped. stability
  - Add'l null: H-mode power threshold, ion loss
  - Larger plasma wetted-area  $A_{\text{wet}}$  : reduce  $q_{\text{div}}$
  - Four strike points : share  $q_{\text{ll}}$
  - Larger X-point connection length  $L_x$  : reduce  $q_{\text{ll}}$
  - Larger effective divertor volume  $V_{\text{div}}$  : incr.  $P_{\text{rad}}$ ,  $P_{\text{CX}}$
- Experiments: TCV, NSTX, DIII-D

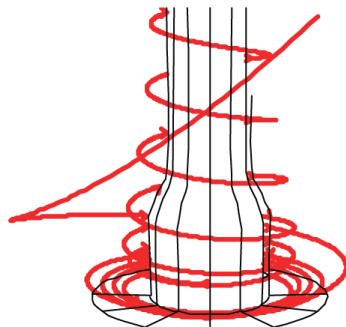


D. D. Ryutov, PoP 14 (2007), 064502;  
Plasma Phys. Control. Fusion 54 (2012) 124050

# Snowflake divertor configurations obtained with existing divertor coils in NSTX and DIII-D

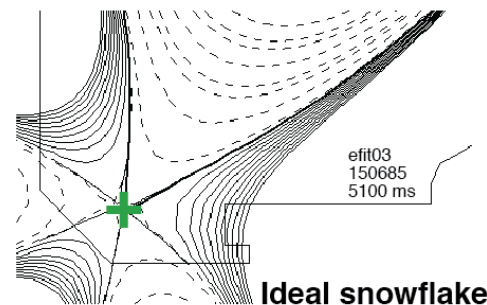


Shot 141241, EFIT02,  
time: 0.905 s,  
normalized flux: 1.005

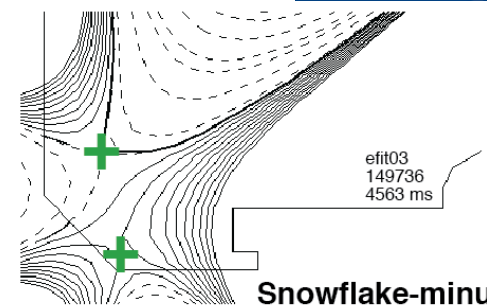


Shot 141240, EFIT02,  
time: 0.905 s,  
normalized flux: 1.005

- Significant increase in the snowflake divertor (cf. standard divertor)
  - Plasma-wetted area (flux expansion)
  - Region of low  $B_p$  field in divertor
  - Magnetic field line length
- Divertor coil currents 0.5-4 kA within safety margins
- Steady-state snowflake configurations sustained for many energy confinement times  $\tau_E$ 
  - NSTX: 0.5 s
  - DIII-D: 3 s



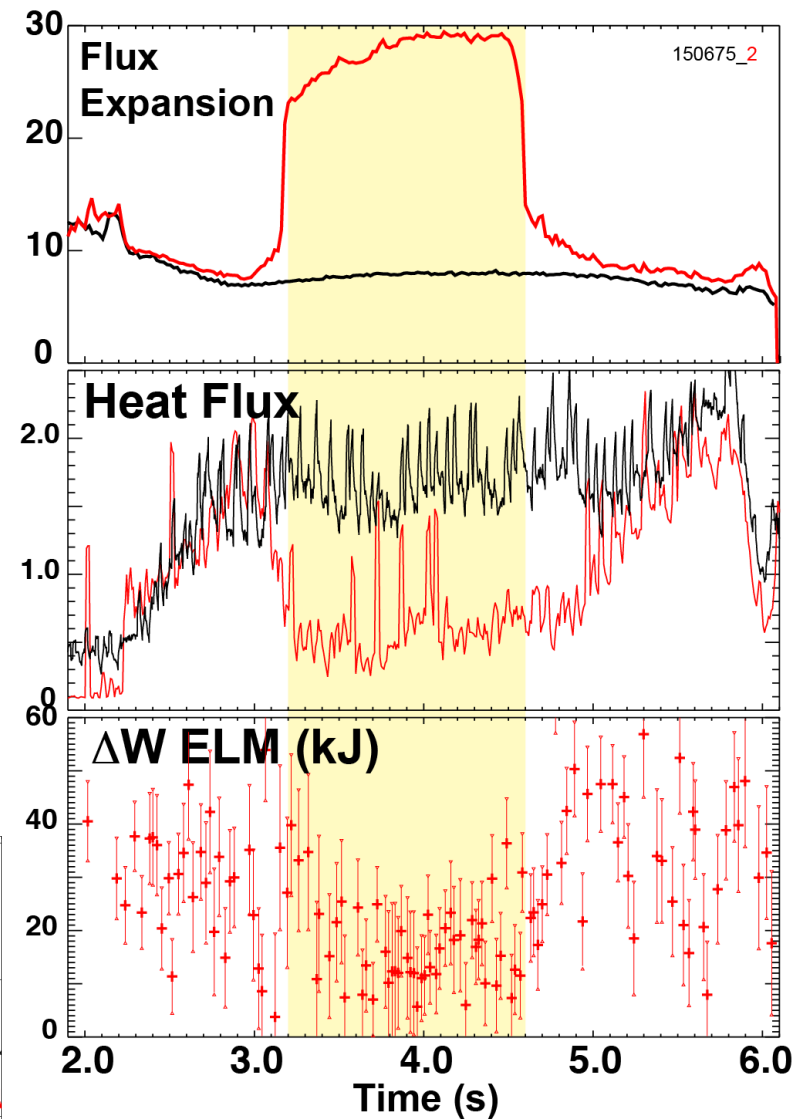
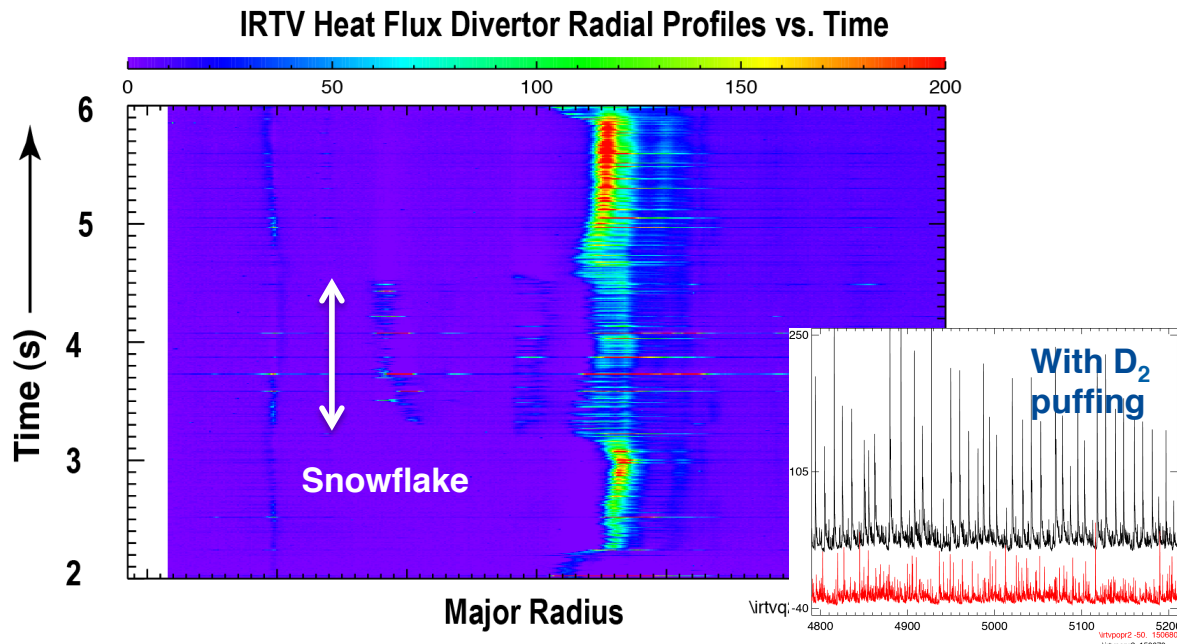
Ideal snowflake



Snowflake-minus

# DIII-D snowflake: good H-mode confinement maintained, heat flux reduction, ELM reduction

- Divertor heat flux reduced 2-3X
- Core confinement ( $H_{89P} > 2$ ) and pedestal constant
- $\Delta W(\text{ELM})$  reduced
- ELM heat flux reduced dramatically with deuterium puffing

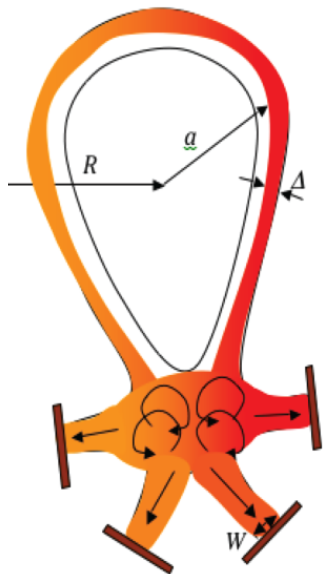


S. L. Allen et al., Paper PD/1-2, IAEA FEC 2012.



# NSTX studies demonstrated compatibility of snowflake divertor with H-mode confinement, heat flux reduction

- NSTX snowflake divertor experiments
  - H-mode confinement unchanged
    - $W_{\text{MHD}} \sim 250$  kJ,  $H_{98}(y,2) \sim 1$ ,  $\beta_N \sim 5$
  - Core impurity reduced by up to 50 %
  - Pedestal stability and ELMs affected
  - Divertor heat flux significantly reduced
    - By up to 80 % between ELMs (from 5-7 to  $\sim 1$  MW/m<sup>2</sup>)
    - By up to 70 % at peak ELM



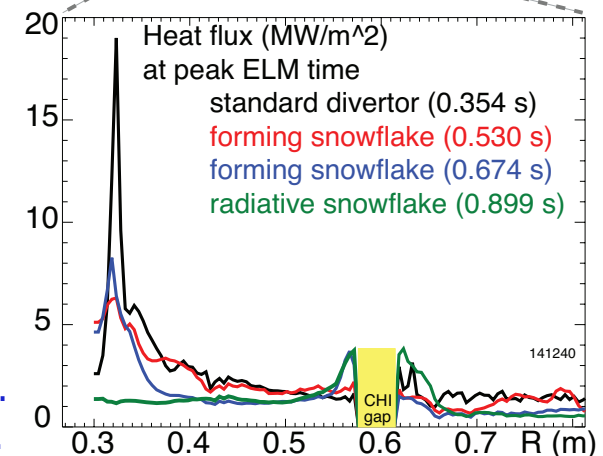
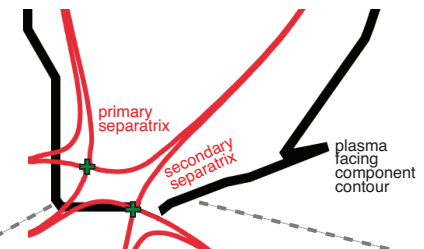
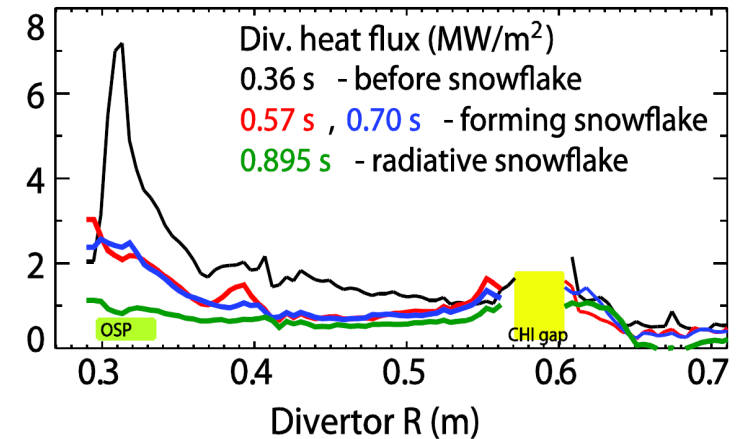
- ELM heat transport theory
  - Reduced surface heating due to increased ELM energy deposition time
  - Convective mixing of ELM heat in null-point region  $\rightarrow$  heat flux partitioning between separatrix branches (strike points)

V. A. Soukhanovskii et al., Nucl. Fusion 51 (2011) 012001.

V. A. Soukhanovskii et al., Phys. Plasmas 19 (2012) 082504.

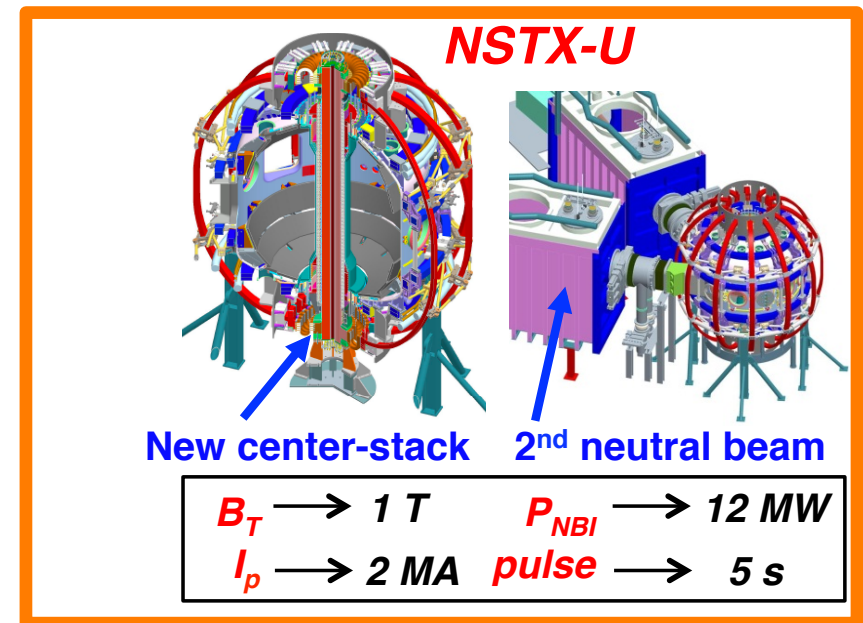
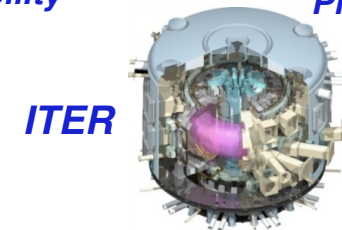
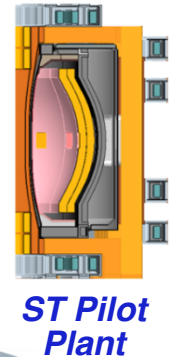
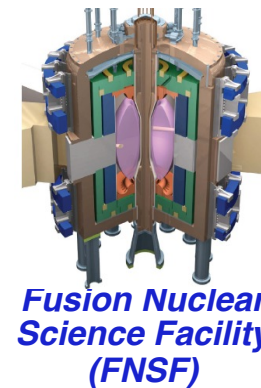
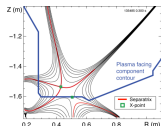
V. A. Soukhanovskii et al., Paper EX/P5-21, IAEA FEC 2012.

D. D. Ryutov et al., Paper TH/P4-18, IAEA FEC 2012



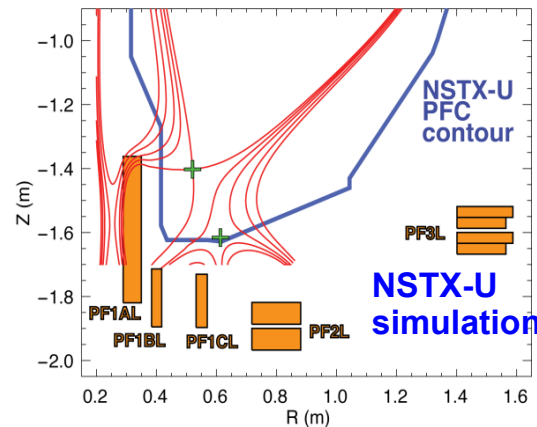
# NSTX-U research aims at predictive understanding needed for fusion energy development facilities

- NSTX-U: Develop key physics understanding to be tested in unexplored, hotter ST plasmas to enable ST-FNSF, ST-Pilot/DEMO, ITER
  - Study high beta plasma transport and stability at reduced collisionality, for extended pulse
  - Prototype methods to mitigate very high heat/particle flux
  - Move toward fully non-inductive operation



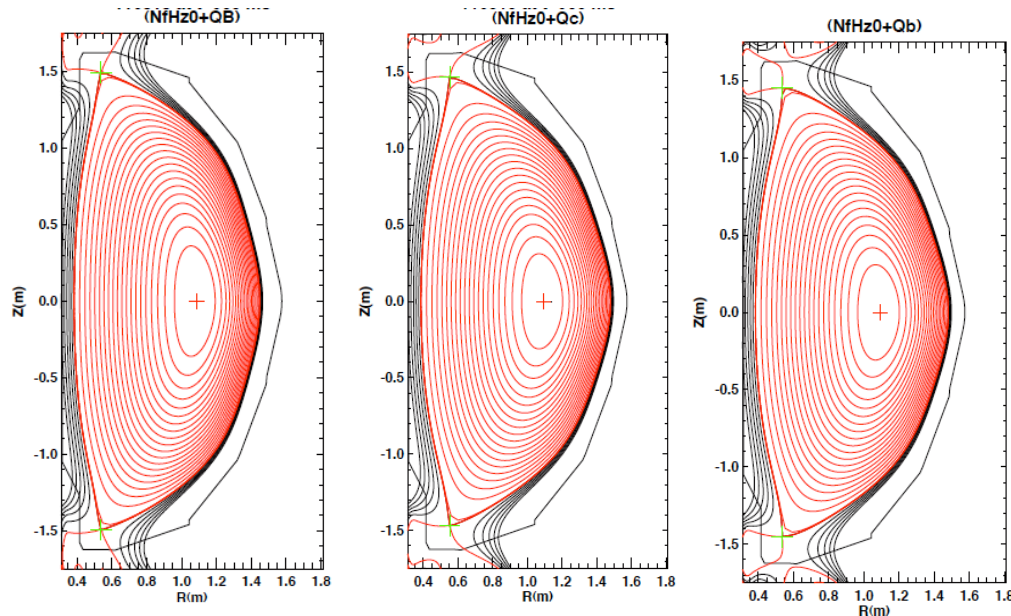
# Snowflake divertor is a leading divertor power exhaust candidate for NSTX-U, modeling projections optimistic

- NSTX-U divertor coils designed to support a variety of snowflake configurations
  - Up-down symmetric possible



- Predictions for 12 MW NBI case with UEDGE code
  - $P_{SOL} = 9$  MW
  - Standard div. heat flux 15-20 MW/m<sup>2</sup>
  - **Snowflake 2-4 MW/m<sup>2</sup>**

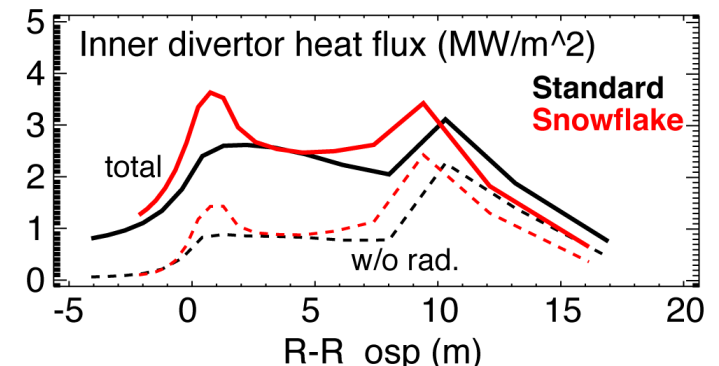
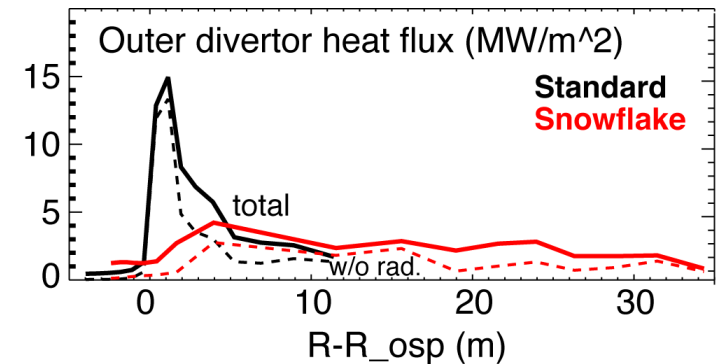
## NSTX-U simulation



NSTX-U standard double-null divertor

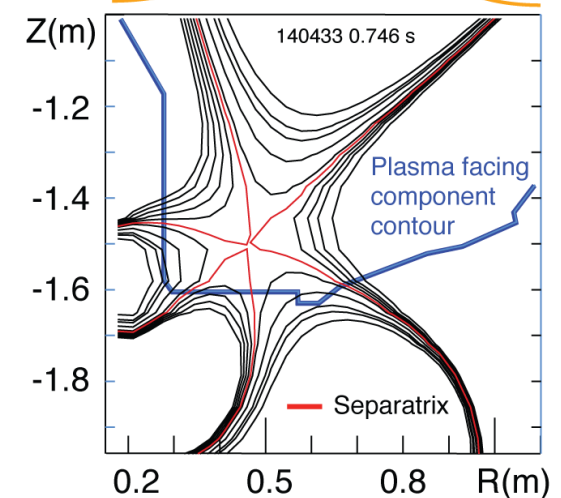
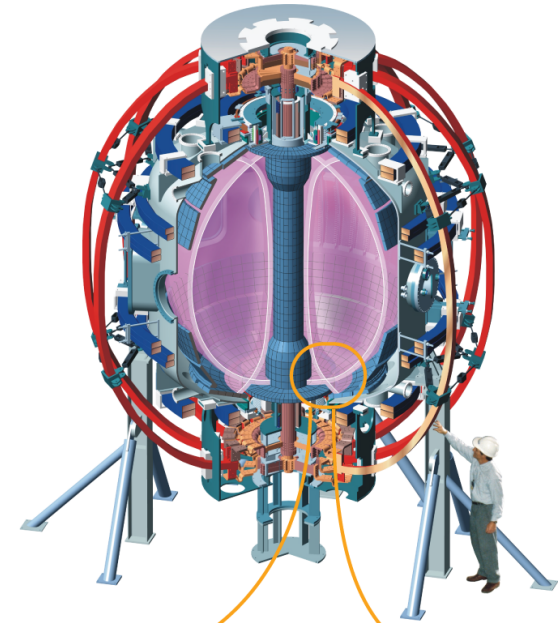
NSTX-U double-snowflake-plus

NSTX-U double-snowflake-minus



# Experiments suggest the snowflake divertor configuration may be a viable divertor power exhaust solution

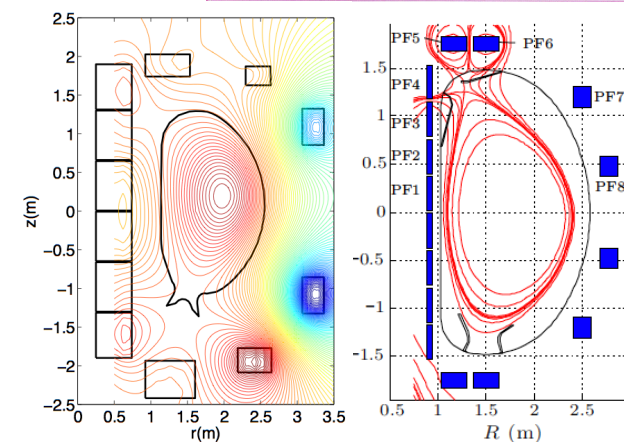
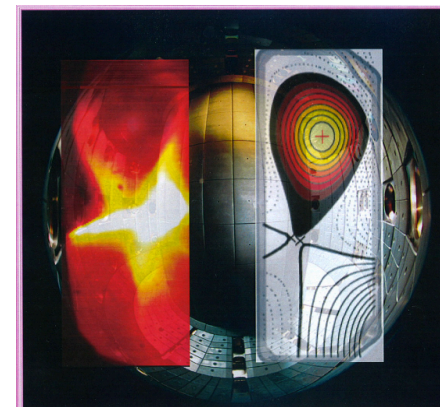
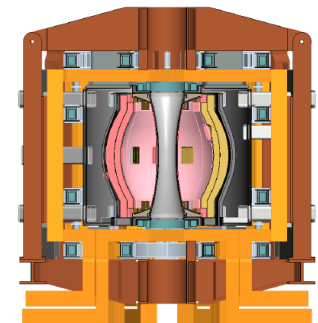
- Results from DIII-D and NSTX:
  - Steady-state snowflake configuration compatible with good H-mode confinement
  - All predicted magnetic geometry properties realized
    - Plasma-wetted area, connection length much higher than in the standard divertor
  - Effects on H-mode pedestal stability and ELM energy
  - Significant reduction of steady-state and ELM peak divertor heat flux
  - Potential to combine with radiative divertor solution
- Future plans:
  - Proposing new experiments in DIII-D in 2013-2014
  - Preparations for experiments in NSTX-U
    - Synergetic effects of snowflake and lithium plasma-facing components
  - Concept development for FNSF and DEMO
    - ST-FNSF planning activity at PPPL





# Snowflake divertor concept rapidly developing into mainstream fusion research direction

- Snowflake divertor concept development by LLNL
  - Theory – D. D. Ryutov et al., 2007 - present
  - Experiment
    - NSTX tokamak, 2009 - 2011
    - DIII-D tokamak, 2012 - present
  - 6 Invited and Oral talks – IEAE FEC, PSI, APS, EPS, ICC conferences
  - R&D 100 Award 2012
- International snowflake divertor research on the rise:
  - Switzerland: TCV tokamak – ongoing experiments
  - China: modeling configurations for HL-2M and CFETR tokamak proposals
  - Italy: snowflake configurations developed for FAST satellite tokamak proposal
  - Britain: planning snowflake configurations for MAST-U tokamak (2015)
  - France: WEST tokamak – planning divertor coils



# Backup slides

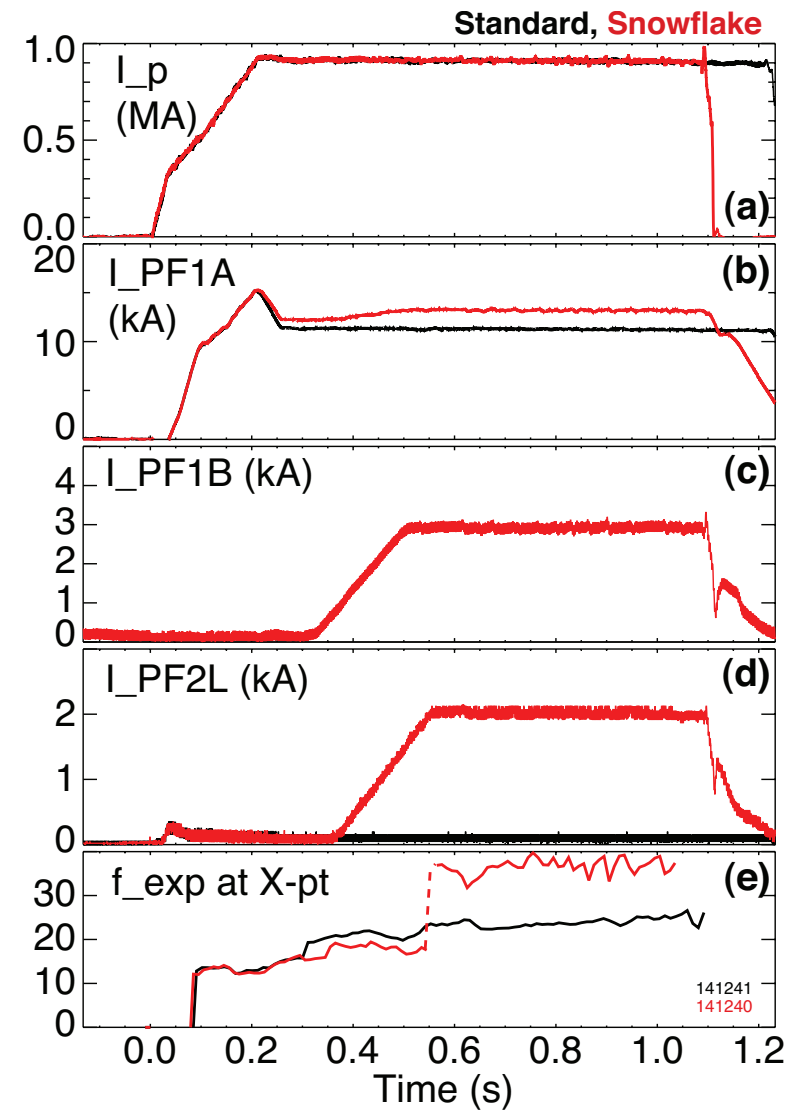
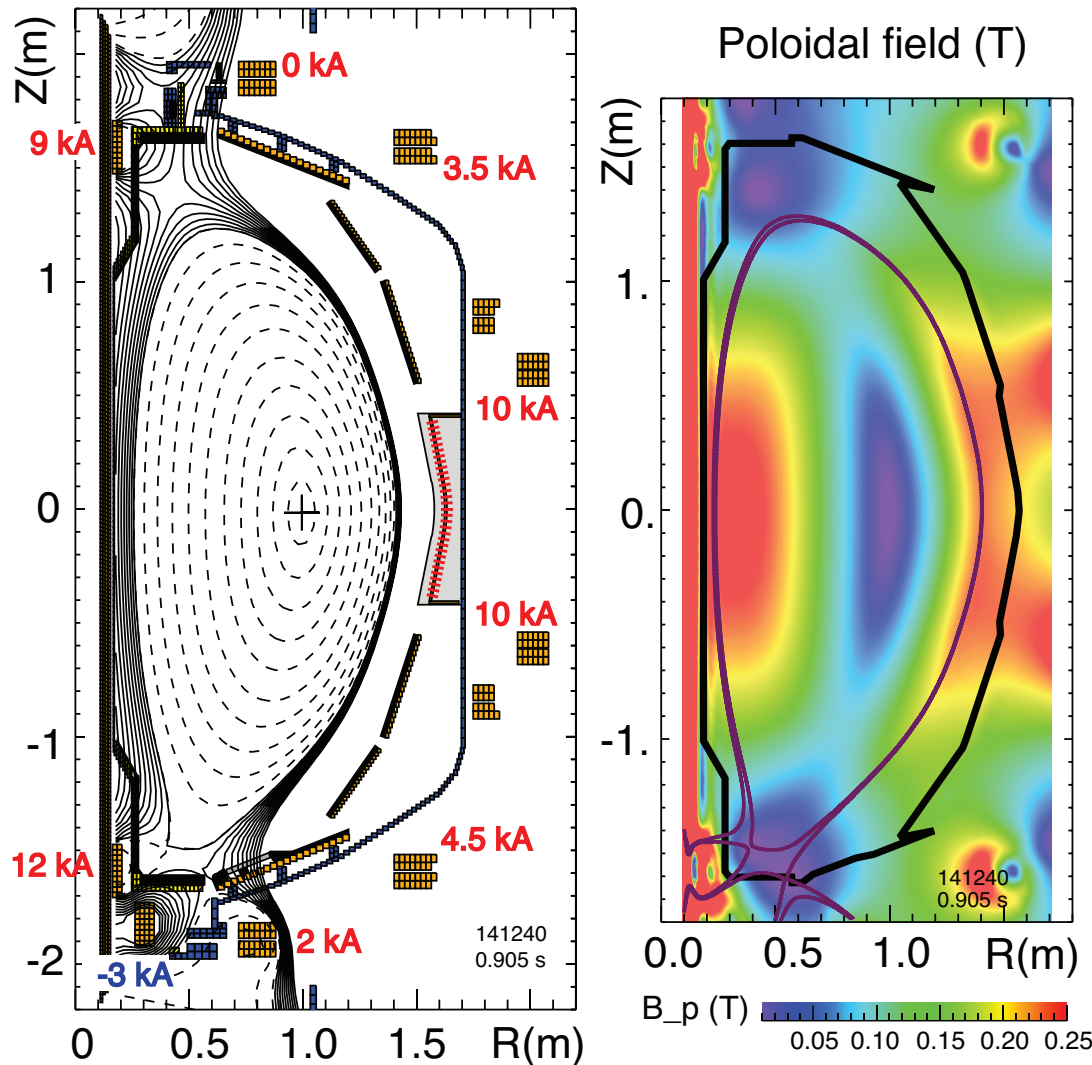
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# Various techniques developed for reduction of heat fluxes $q_{\parallel}$ (divertor SOL) and $q_{peak}$ (divertor target)

$$q_{peak} \simeq \frac{P_{SOL}(1 - f_{rad})f_{geo} \sin \alpha}{2\pi R_{SP} f_{exp} \lambda_{q_{\parallel}}} \quad A_{wet} = 2\pi R f_{exp} \lambda_{q_{\parallel}}$$
$$f_{exp} = \frac{(B_p/B_{tot})_{MP}}{(B_p/B_{tot})_{OSP}}$$

- Promising divertor peak heat flux mitigation solutions:
  - Divertor geometry
    - poloidal flux expansion
    - divertor plate tilt
    - magnetic balance
  - Radiative divertor
- Recent ideas to improve standard divertor geometry
  - X-divertor (M. Kotschenreuther *et. al*, IC/P6-43, IAEA FEC 2004)
  - Snowflake divertor (D. D. Ryutov, PoP 14, 064502 2007)
  - Super-X divertor (M. Kotschenreuther *et. al*, IC/P4-7, IAEA FEC 2008)

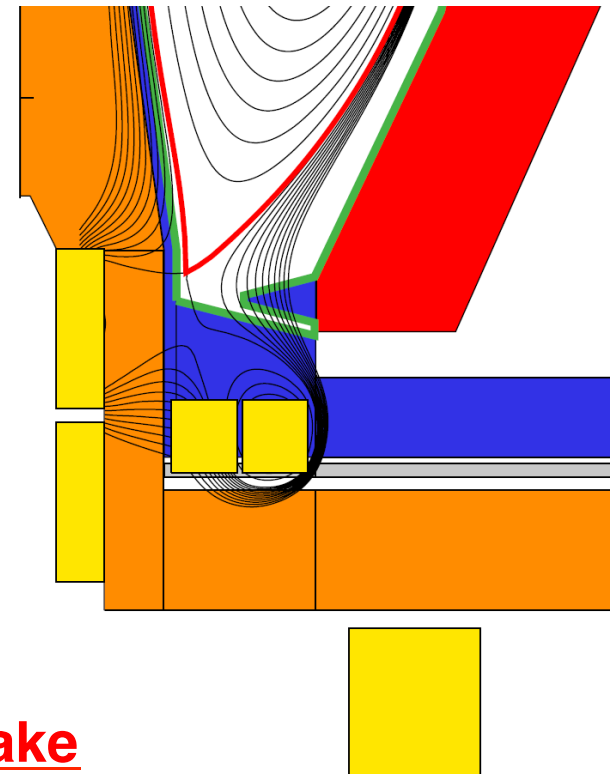
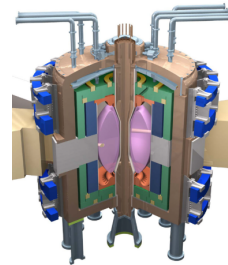
# Snowflake divertor configurations obtained with existing divertor coils, maintained for up to $10 \tau_E$





# Snowflake divertor designs are studied for next-step spherical tokamak based devices

- ST-FNSF development studies are quantifying performance dependence on size
- Building on achieved/projected NSTX/NSTX-U performance and design
- Divertor PF coil configurations identified to achieve high  $\delta$  while maintaining peak divertor heat flux  $< 10\text{MW/m}^2$



Parameter	Fusion Nuclear Science Facility
Major Radius $R_0$ [m]	1.3
Aspect Ratio $R_0 / a$	$\geq 1.5$
Plasma Current [MA]	4 – 10
Toroidal Field [T]	2 – 3
Auxiliary Power [MW]	22 – 45
P/R [MW/m]	30 – 60
P/S [MW/m <sup>2</sup> ]	0.6 – 1.2
Fusion Gain Q	1 – 2

## Snowflake

- Flux expansion = 40-60,  $\delta_x \sim 0.62$
- $1/\sin(\theta_{\text{plate}}) = 1-1.5$
- Good detachment (NSTX data) and cryo-pumping (NSTX-U modeling)

J. Menard et. al., Paper FTP/3-4, IAEA FEC 2012